Performance of Silicon carbide whisker reinforced ceramic inserts on Inconel 718 in end milling process

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Abstract. An experimental investigation is planned in order to study the machinability of Inconel 718 with silicon carbide whisker reinforced ceramic inserts in end milling process. The relationship between the cutting speed, feed rate, and depth of cut against the response factors are studied to show the level of significance of each parameter. The cutting parameters are optimized by using Taguchi method. Implementing analysis of variance, the parameter which influences the surface roughness the most is determined to be the cutting speed, followed by the feed rate and depth of cut. Meanwhile, the optimal cutting condition is determined to have high cutting speed, low feed rate, and high depth of cut in the range of selected parameters.

1. Introduction

Nickel-based superalloys have always been a significant usage in the aircraft and nuclear industry due to its excellent thermal resistance which maintains steady mechanical properties even at elevated temperature. However, being classified as a difficult-to-cut material, machining of nickel-based superalloy still remains as a challenge for various engineering experts in the industry due to the fact that it often generates numerous concerns and problems.

The constant demand to increase productivity and quality in machining operation has lead to the development of ceramic tools. Ceramic tools excel in high cutting speed and are much more suitable in high speed machining. In the industry field, the whisker-reinforced ceramic tools are mostly limited to semi-finishing and roughing operations due to their spontaneous failure and less predictable tool life [1]. Due to the reason that whisker reinforced ceramic are considerably expensive, it is fundamentally important to optimize the cutting parameters as finely as possible such that production requirements could be achieved.

Tool wear can be defined as a complicated phenomenon which is unavoidable and undesirable in every machining process. More importantly, tool wear has a strong presence in affecting production costs and also surface integrity of a machined component. The phenomenon where the chip and tool surface withstands high temperature and high relative velocity in addition to the chemical affinity of silicon carbide whiskers and Alloy 718 can be interpreted as leading to adhesion wear mechanism [2]. The resistance to depth-of-cut notch wear of the whisker-reinforced ceramic tool has been found to be greater than that of other Al_2O_3 based ceramic tools because of the toughening effect of the whiskers [4]. On the other hand, surface roughness is also a significant factor in machining as it indicates the surface quality of a machined part. Surface roughness is said to be related to tool wear in the sense of being directly affected by it whereby serious tool wear basically increases the roughness of the surface. Common cutting parameters include tool material, coating material, cutting speed, depth of cut, and feed rate. Being said, optimization of these parameters is very important to achieve minimum surface roughness and tool wears which relates to the aspect of cost reduction.

Design of experiments has the ability to predict the output with the minimum number of experiments by considering the experimental limits, specific conditions, and mathematical analysis [5]. The optimization of cutting parameters affecting surface roughness can be dealt with various methods such as Taguchi method and

multiple regression models. It is essential for every machining process to select optimal machining conditions due to the fact that it is a key factor in achieving higher machining efficiency. Taguchi method represents a method totally based on statistical design of experiments.

2. Taguchi Design

The Taguchi method represents an experimental design technique, which is very useful and effective in experimental investigation by significantly reduces the number of experimental runs. Hence, this technique is able to significantly reduce the time required for experimental investigation due to its ability to investigate multiple factors on performance and also the influence of individual factors [3]. In this study, the orthogonal array is formed with three factors while implementing three different levels. The three factors include process parameters of cutting speed, feed rate, and depth of cut. The L9 orthogonal array of this study mainly investigates the main effects of the process parameter towards surface roughness and flank wear, therefore the interaction between process parameters is neglected. Therefore, after the orthogonal array has been selected, the next step would be proceeding to run the experiment. Results of the cutting experiments are studied by using the S/N ratio and ANOVA. Based on the results of the analyses, optimal cutting parameters for minimum surface roughness and flank wear are obtained and verified.

3. Experimental Methodology

The experiments were carried out in end milling process without using coolant. End milling process is considered as the most common machining process in various industries due to its versatile and rapid machining. The work piece material that is employed in this research project is Inconel 718, a type of nickel-based super alloy where the work piece has a dimension of 200mm length, 100mm width, and 15.875mm thickness. Silicon carbide whisker reinforced ceramic inserts collected from SSANGYONG company graded SW500. This grade of ceramic insert is a newly developed ceramic cutting tool where the company state that it has excellent flank and notch wear resistance in high speed cutting especially in machining high temperature alloy and high nickel alloy.

Table 1: Range of cutting parameter values

Parameter	Unit	Level of parameter		
		Level 1	Level 2	Level 3
Cutting speed	m/min	200	250	300
Feed rate	mm/rev	0.05	0.07	0.09
Depth of cut	mm	0.50	0.70	0.80

Table 2: Parameter level for L9 orthogonal array

Experiment Run	Process parameters		
	Cutting speed	Feed rate	Depth of cut
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

The process parameters range, selection of levels are listed in Table 1, which is decided based on the recommendation from the tool suppliers and literature. The Taguchi L9 orthogonal array defines the 9 tests for three cutting parameters are listed in Table 1. The surface roughness of the work piece is measured by using Mitutoyo SJ-301 surface roughness tester.

4. Results and Discussion

4.1. S/N ratio ANOVA results

The signal-to-noise ratio is determined to identify optimal control factor settings which make the process robust. S/N ratio transformation preferred is smaller the better characteristics, which follows the formula of equation 1 [6],

$$S/N = -10 \log \frac{1}{n} \left(\sum y^2 \right).$$

(1)

Based on the analysis of the S/N ratio, the greater S/N ratio corresponds to the smaller variance of the output characteristic around the desired value. Hence, as illustrated in the S/N response graph above, the highest S/N ratio for surface roughness are obtained at cutting speed level 3 (300m/min), feed rate level 1 (0.05mm/rev), and depth of cut level 3 (0.8mm). Therefore, the optimal cutting parameters to obtain better surface roughness can be determined to have high cutting speed, low feed rate, and high depth of cut.

Table 3: Surface roughness experiment results

Experiment run	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Surface roughness R_a (µm)	S/N ratio
1	200	0.05	0.50	1.79	-5.06
2	200	0.07	0.70	1.67	-4.45
3	200	0.09	0.80	1.78	-5.01
4	250	0.05	0.70	1.74	-4.81
5	250	0.07	0.80	1.80	-5.11
6	250	0.09	0.50	1.68	-4.51
7	300	0.05	0.80	1.40	-2.92
8	300	0.07	0.50	1.72	-4.71
9	300	0.09	0.70	1.75	-4.86
Total					-41.44

Table 4: Average S/N ratio for surface roughness

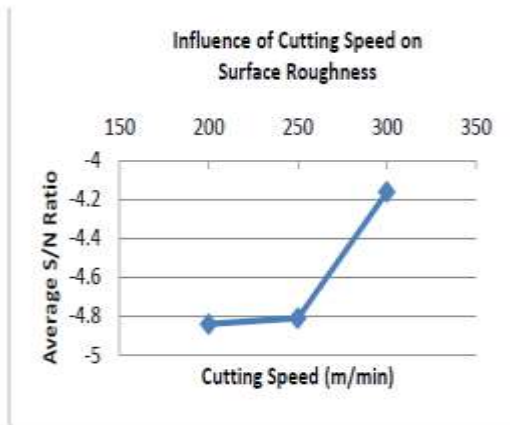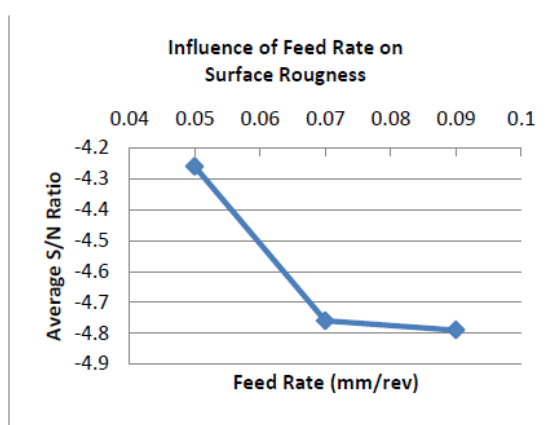| Average S/N ratio for Surface roughness			
Parameter	Level 1	Level 2	Level 3
Cutting speed	-4.84	-4.81	-4.16
Feed rate	-4.26	-4.76	-4.79
Depth of cut	-4.76	-4.71	-4.35

Figure 1: Influence of cutting speed

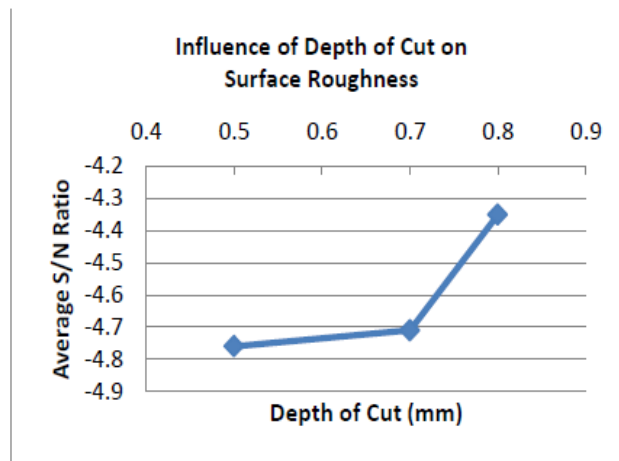**Figure 2**: Influence of feed rate

Figure 3: Influence of depth of cut

Table 5 shows the analysis of variance (ANOVA) results with 95% confidence level in order to determine the significant parameter. Through the ANOVA analysis, the contribution for each parameter is identified where cutting speed contributes 24.25%, feed rate having 14.53%, and depth of cut having 8.39% contribution factor. This indicates that the cutting speed is the most significant parameter in influencing the surface roughness followed by the feed rate and lastly the depth of cut.

Table 5: Results for analysis of variance

Analysis of variance for surface roughness				
Parameter	Degree of freedom	Sum of squares	Mean square	Contribution (%)
Cutting speed	2	0.8770	0.4385	24.25
Feed rate	2	0.5256	0.2628	14.53
Depth of Cut	2	0.3033	0.1517	8.39
Error	2	1.9105	0.9553	52.83
Total	8	3.6164		100

4.2. Tool wear results

Wear patterns observed in cutting tools results from the combined effect of different wear mechanisms involved in sliding friction occurring at the contact interface between tool, chip and machined surface. In the case of machining nickel-based super alloys, the most known tool wear pattern would be flank wear and notch wear. The main concern and focus on the tool wear in this experiment would be to determine the results of flank wear which is generally caused by the fracture in ultra- high speed cutting process. Basically, all of the figures of tool wear shown in Figure 4, do not seem to illustrate a significant difference as all nine set of cutting tools display similar tool wear and pattern where tool fracture had occurred.
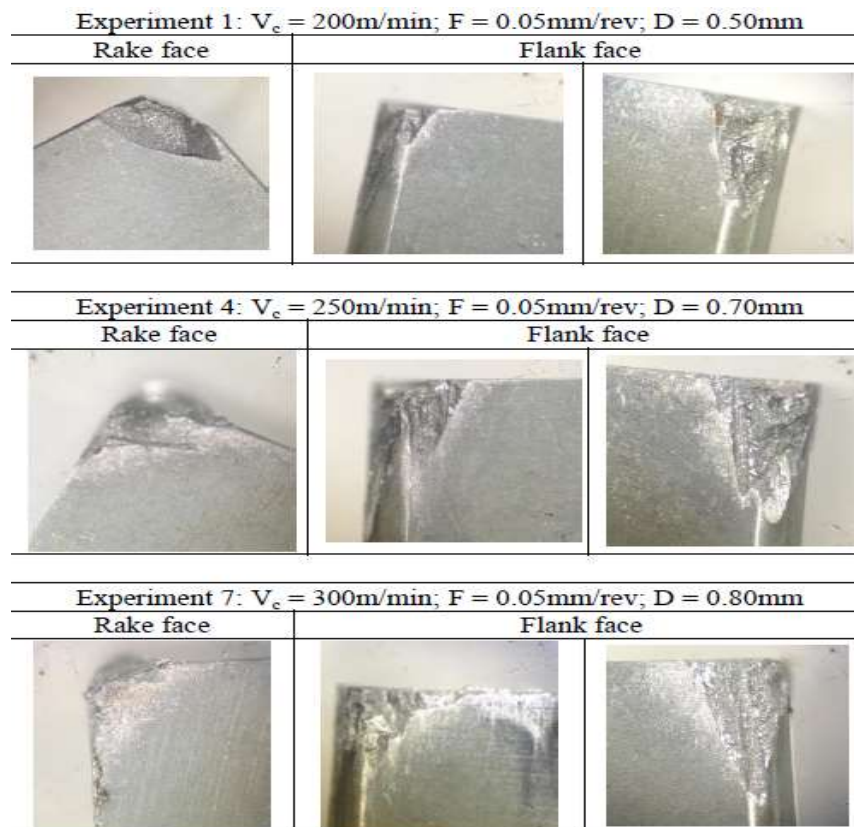

Figure 4: Tool wear pattern

Tool fracture would occur with the increase in the volume of metal removal, as the tool is damaged progressively by the alternating mechanical stress and thermal stress. This is most probably due to the major disadvantages of ceramic tools where they have low fracture toughness while being low resistance to mechanical shock as well. Furthermore, by observing the respective fracture, the fracture can be said to be too serious for further machining which indicates that the tool life of the cutting tool had been reached.

5.   Conclusion

There are several conclusions which can be drawn for this research work. Firstly, the S/N ratio analysis identifies that the optimal cutting condition for the experiment is by having high cutting speed, low feed rate, and high depth of cut. Analysis of Variance (ANOVA) proves that cutting speed is the factor that influences the surface roughness the most with a contributing factor of 24.25%, followed by feed rate of 14.53% and depth of cut with 8.39%. Although the main focus on tool wear in this project is stated to be on flank wear, however the results for tool wear is too extreme and is considered as tool failure whereby the tool fracture had been too serious. Therefore, it can be concluded that the SSANGYONG SW500 graded whisker reinforced ceramic cutting insert is suit only for rough machining of Inconel 718 due to extreme tool wear and unfavorable surface roughness.

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